MEASUREMENT OF PLASMA TEMPERATURE AND

ELECTRON DENSITY DISTRIBUTIONS

USING MILLIMETER WAVES

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Summary 15528

A method for obtaining good resolution in the measurement
of electron density and temperature variations in a thermal
plasma of cylindrical cross section is described. The tech-
nique involves the division of a plasma into concentric zones
and evaluation of the attenuation constant in each zone from
measured attenuation losses. Results of measurements made on
a cyanogen-oxygen flame at 61.2 Gc are given, and correlation
of the peak and average temperature values with spectroscopic
and K-band measurements is shown.

Introduction

As a result of high-temperature plasma research, various tech-

niques have been developed to measure the properties of an ionized gas.

These methods fall into the following categories: metallic current

probes, electron beam probes, optical measurements of emission line

broadening and of emission spectra, and schemes employing microwave

interactions with the medium. Probe techniques are often not appli-

cable due to a lack of suitable theories for interpreting the data

they supply, and optical measurements may be limited because of low

spectral line intensity. Therefore, efforts have been extended toward

the use of microwave diagnostics to measure plasma characteristics.

Of particular interest is the measurement of plasma temperature and

electron density. Some previous studies of plasma temperature and

electron density that have been made[1,2] had, in general, limited resolution and resulted in average values for the electron density and temperature.

This paper describes a high-resolution millimeter wave technique for studying electron density and temperature distributions in non-reflecting stratified cylindrical plasmas. The results of survey measurements made with a 60 to 70 Gc system on a stoichiometric, cyanogen-oxygen flame which forms a 3-inch-diameter subsonic jet at atmospheric pressure will be given.

Survey Technique

The electron density and temperature of a thermal plasma can be deduced from the electromagnetic properties of the plasma and Saha's equation. The electromagnetic properties relate the propagation constants, attenuation constant α and phase constant β, of a plasma to the electron density N_e and collision frequency ν. Saha's equation relates the electron density to the temperature in an ionized gas for a given ionization potential and total gas pressure. Thus, with a measured attenuation constant, a given collision frequency, and a knowledge of gas constituents, the electron density and temperature can be determined.

1. Rudlin, Leonard, "Preliminary results of a determination of temperatures of flames by means of K-band microwave attenuation," NACA RM E51G20, 1951.

2. Huber, Paul W., and Gooderum, Paul B., "Experiments with plasmas produced by potassium-seeded cyanogen oxygen flames for study of radio transmission at simulated reentry vehicle plasma conditions," NASA TN D-627, 1961.

To arrive at a reasonable survey technique, the following plasma conditions are assumed:

1. The plasma is nonreflecting at the frequency used.

2. The plasma is cylindrical, having radial variations only.

3. The ratio of plasma diameter to width of antenna receiving aperture is large.

4. The ionization potential, total gas pressure, and collision frequency of the plasma are known.

If the above conditions are met, the electron density and temperature variations in a plasma can be determined by measuring the insertion loss experienced as the plasma traverses between two microwave horns normal to the direction of propagation. The measuring apparatus is shown in figure 1.

Since theory is based on attenuation per unit length, a model for evaluating effective path lengths will be helpful in converting from measured attenuation in db to attenuation per unit length in db/cm. Figure 2 shows a cylindrical plasma divided into five concentric zones of constant attenuation per unit length with a width equal to that of the receiving horn aperture.[3] Each zone is further divided as shown by the outer zone in figure 3. The strips in figure 3 are of unit width; therefore, lengths can be assigned to these strips which are equal to the intersected area on the cylinder. An effective path length in a zone, then, is obtained by averaging the lengths (or areas) of the strips in that zone. The area of a strip in a particular zone

3. The number of zones depends on the ratio of the plasma diameter to the width of antenna receiving aperture. Figure 2 represents the model used to evaluate laboratory tests.

is obtained from a table of area coefficients $A_{k,j}$ for given values
of r_k and x_j.[4]

Once the effective path lengths and measured attenuation losses
are known, the attenuation constant for each zone can be determined
from the following expression:

$$\alpha_n = \frac{\sum_{k=1}^{n} db_k - \sum_{i=0}^{n-1} \alpha_i l_i}{l_n}$$

where the subscript n designates the zone starting with $n = 1$ for
the outer zone.

Using the attenuation constants thus obtained, the electron
density and temperature in each zone are found from theoretical plots
of attenuation per unit length versus electron density and electron
density versus temperature for the plasma being surveyed.

Results

The following results were measured on a stoichiometric cyanogen-
oxygen flame at a frequency of 61.2 Gc.[5] The ratio of flame diameter
to width of receiving horn antenna was 10:1, allowing the flame to be
divided into five concentric zones each having a width of 0.3 inch.

The measured attenuation experienced as the flame traversed
between the horns is shown in figure 4. Application of this data to
the assumed plasma model yields the attenuation constant for each zone.

4. Wm. J. Pearce, Conference on Extremely High Temperatures, March
1958.
5. A description of this plasma is given in the Appendix.

The resulting electron density and temperature distributions, from figures 7 and 8 in the appendix and values obtained for the attenuation constants, for the cyanogen-oxygen flame are shown in figure 5.

Although some fluctuations were present in the flame, the survey technique gave a distribution which follows a bell-shaped curve with a maximum temperature at the center of $4,470^\circ$ K and a minimum of $4,145^\circ$ K at the edge. Integrating the area under the curve in figure 5 gives an average temperature of $4,180^\circ$ K. These values have been correlated with previous microwave measurements at K band as reported in NASA TN D-627 and recent spectroscopic measurements. The K-band measurements gave an average value of temperature of about $4,200^\circ$ K for this flame, and the spectrographic measurements gave a peak value of $4,500^\circ$ K at the center of the flame.

A noteworthy advantage of this technique for the results given is the use of a calculated collision frequency. If the collision frequency is in error by an order of magnitude, the attenuation constant versus electron density curve will be shifted only slightly resulting in small errors of a few percent for the electron density and temperature values.

Concluding Remarks

Electron density and temperature distributions obtained from 61.2 Gc attenuation measurements have been presented for a 3-inch-diameter cyanogen-oxygen flame. The ratio of flame diameter to width of receiving horn aperture (0.3 inch) was 10:1, allowing the flame to be sampled in 0.3-inch segments.

Correlation of the peak and average temperature values with other techniques shows that the survey technique described is a useful means for obtaining electron density and temperature variations in a cylindrical plasma.

Appendix

The test plasma used to evaluate the survey technique is a stoi-chiometric cyanogen-oxygen flame which forms a 3-inch-diameter subsonic jet at atmospheric pressure. The calculated collision frequency for this flame is 6×10^{10} sec^{-1}; and application of Saha's equation to a stoichiometric equilibrium combustion of cyanogen and oxygen gives a plot of temperature versus electron density as shown in figure 6.[6] The maximum temperature calculated for this flame assuming no heat loss is 4,850° K. This corresponds to a maximum value for the electron density of 7.4×10^{12}/cc.

Examination of the electromagnetic properties of a plasma at a frequency of 61.2 Gc and for a collision frequency of 6×10^{10} sec^{-1} yields the following:

1. The cyanogen-oxygen flame is nonreflecting for electron den-sities less than 10^{13}/cc.

2. A plot of electron density versus attenuation constant is as shown in figure 7.

By combining figures 6 and 7, a useful plot of temperature versus attenuation constant can be made; this plot is shown in figure 8.

Therefore, the cyanogen-oxygen flame meets the necessary require-ments outlined and a temperature distribution can be made by measuring transmission loss as a function of flame diameter.
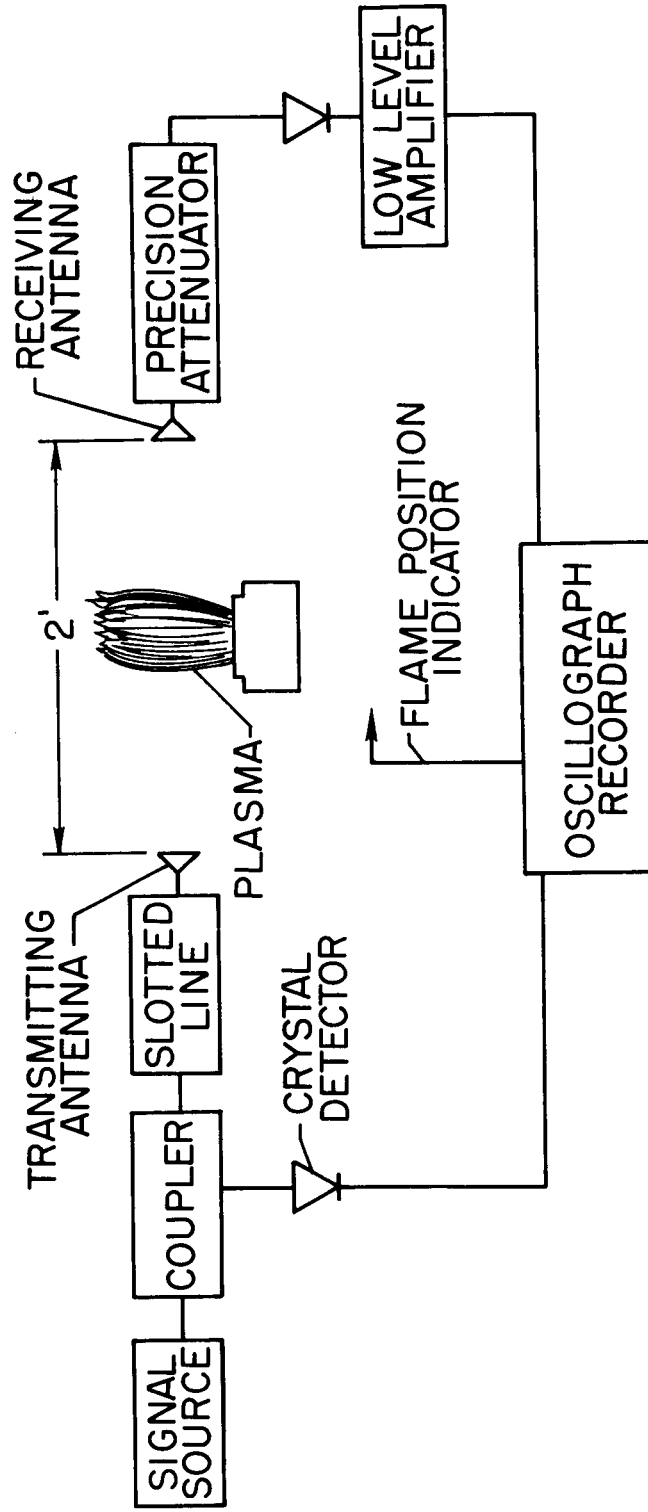
Figure 1.- Schematic diagram of measuring system.
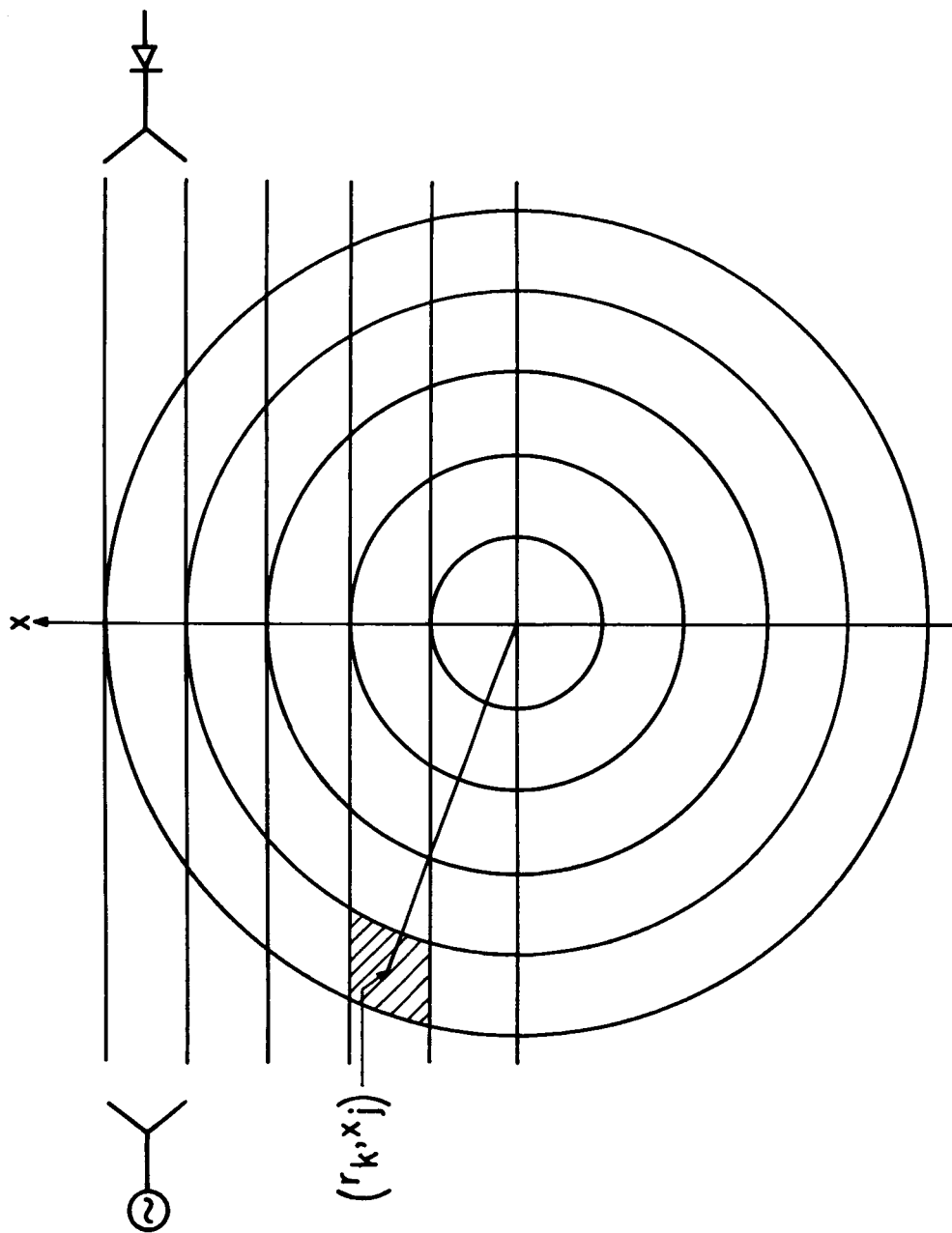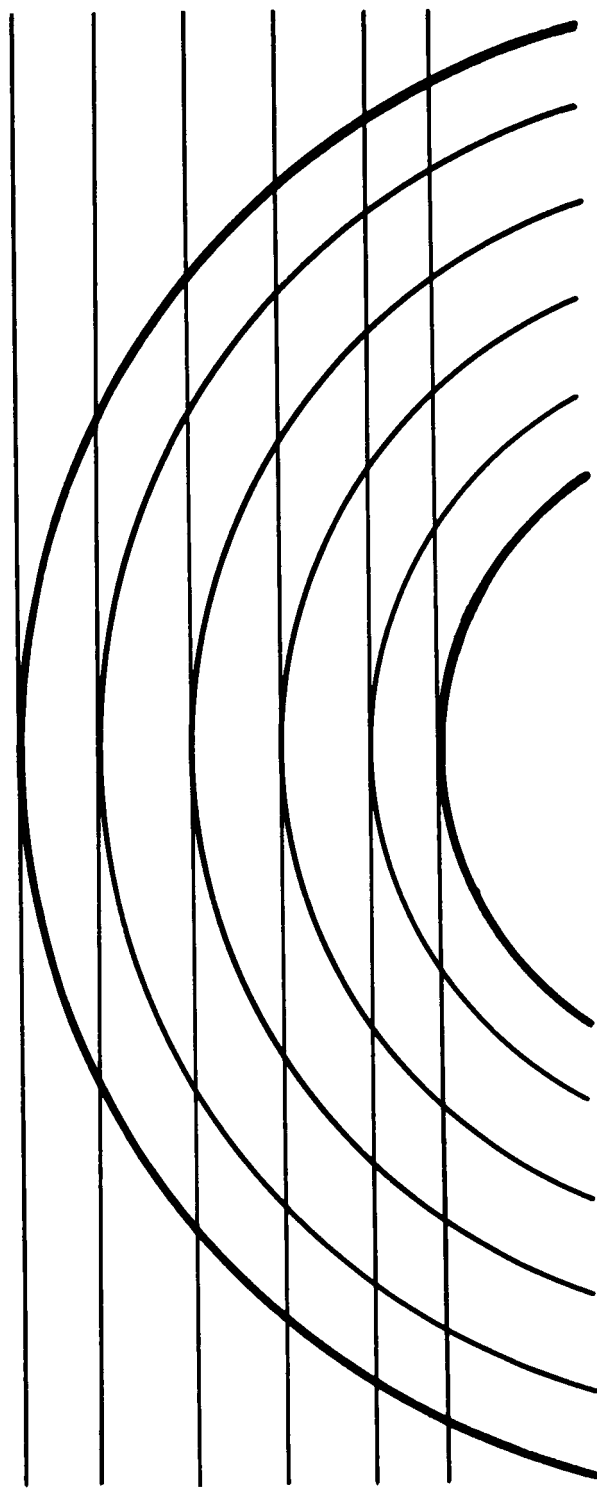
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Figure 2.- Assumed model of a cylindrical plasma.

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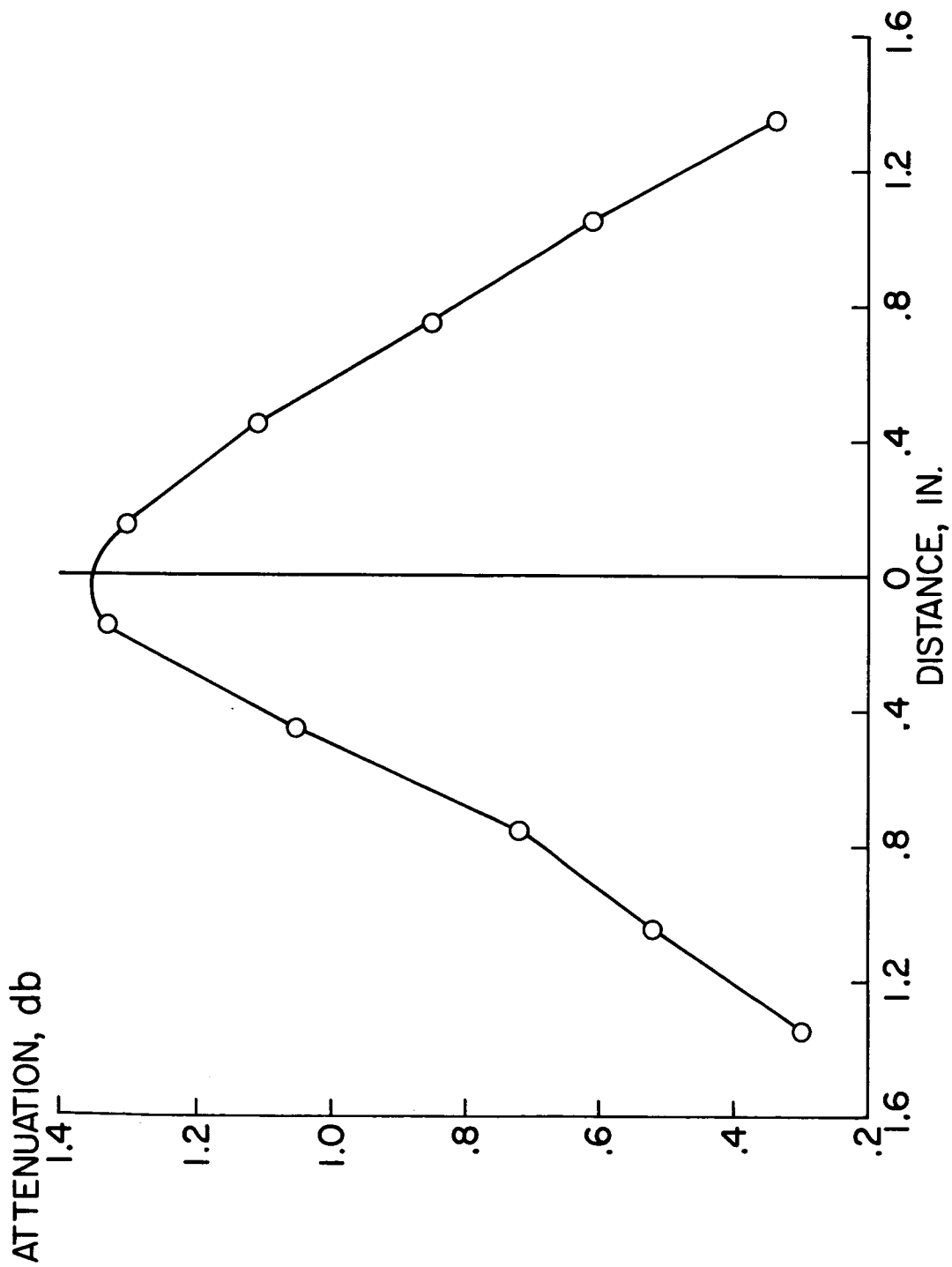Figure 3.- Enlargement of the outer zone of assumed model.

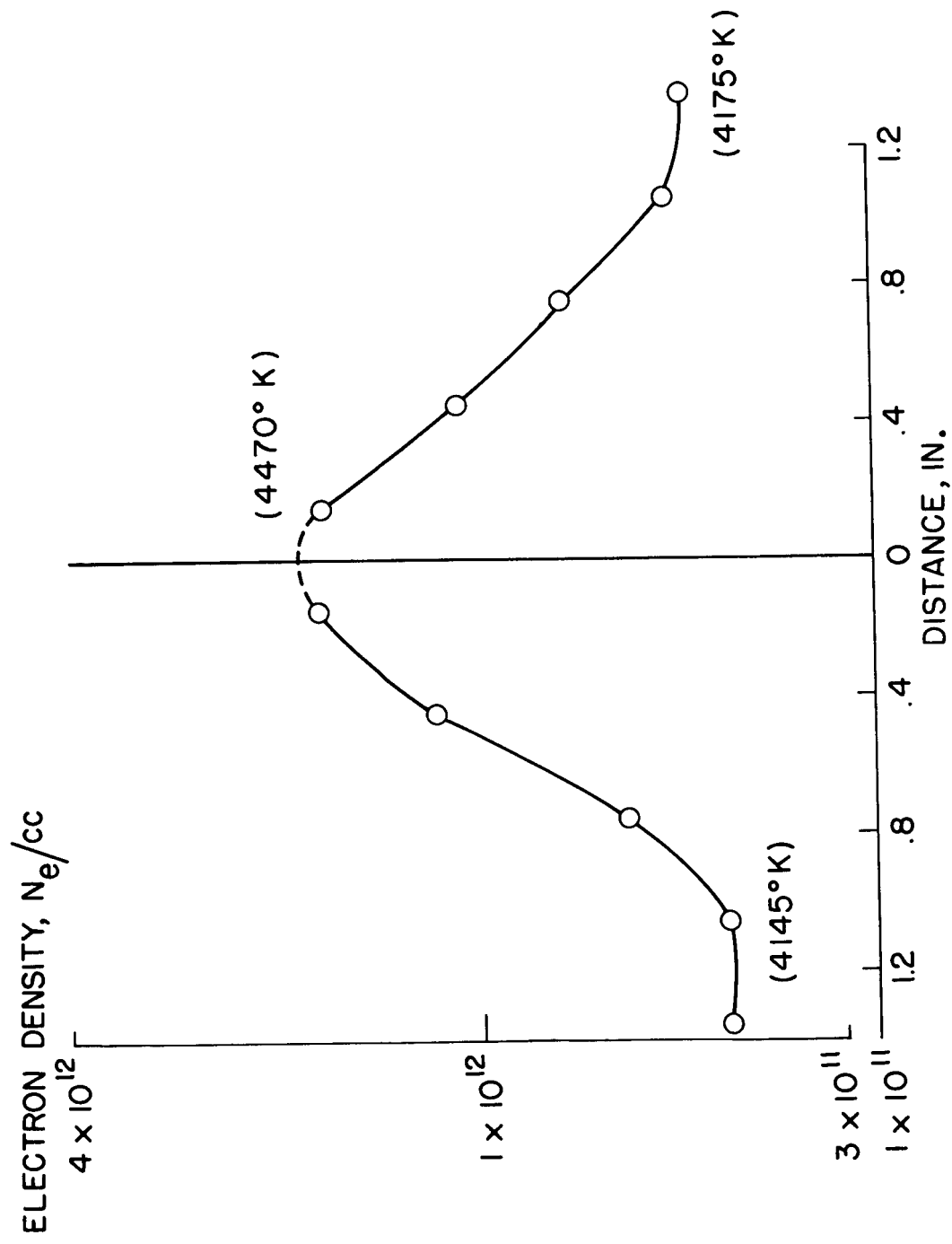Figure 4.- Transverse survey of cyanogen-oxygen flame at 61.2 Gc.

Figure 5.- Electron density and temperature distributions in a cyanogen-oxygen flame.
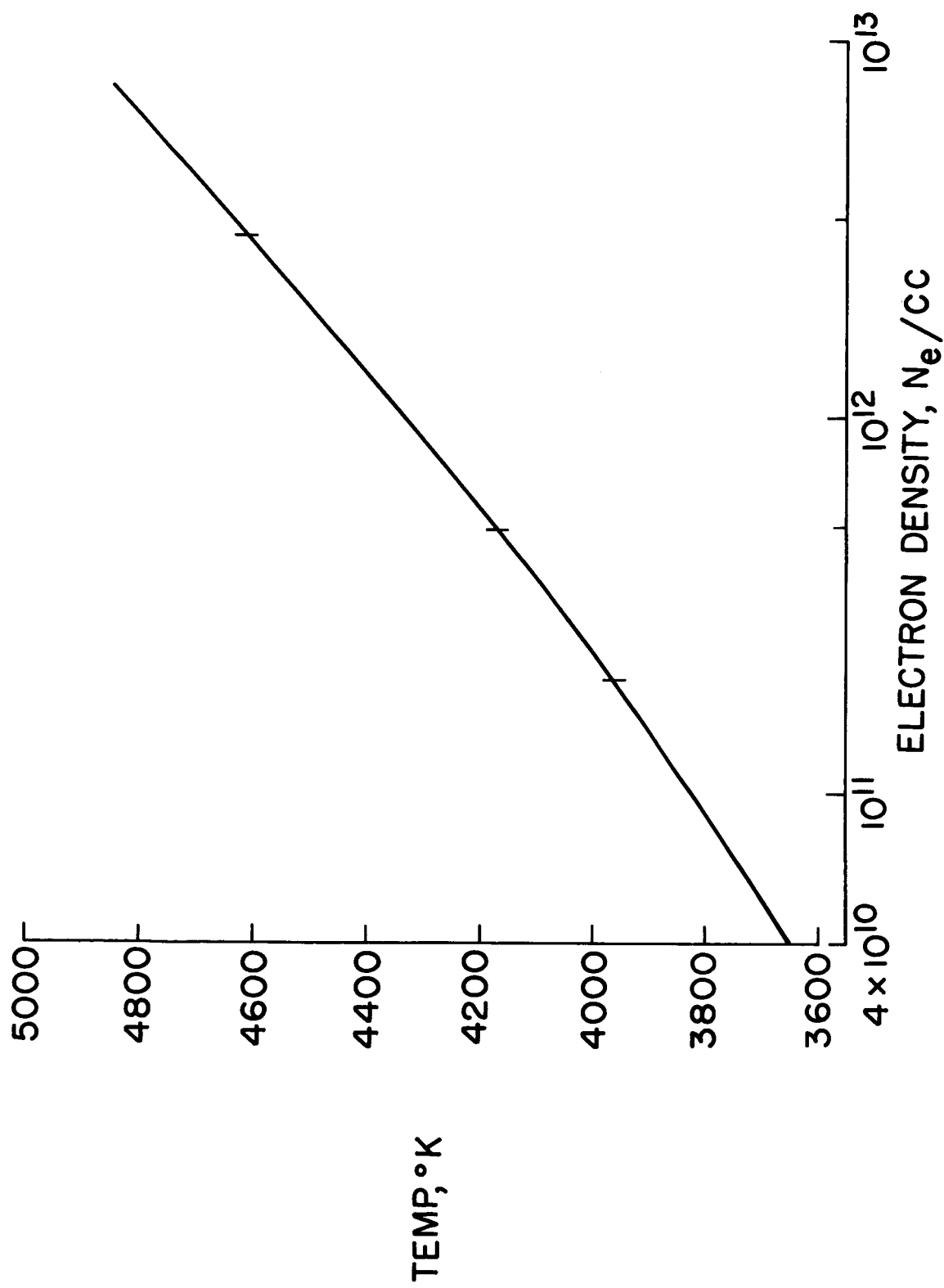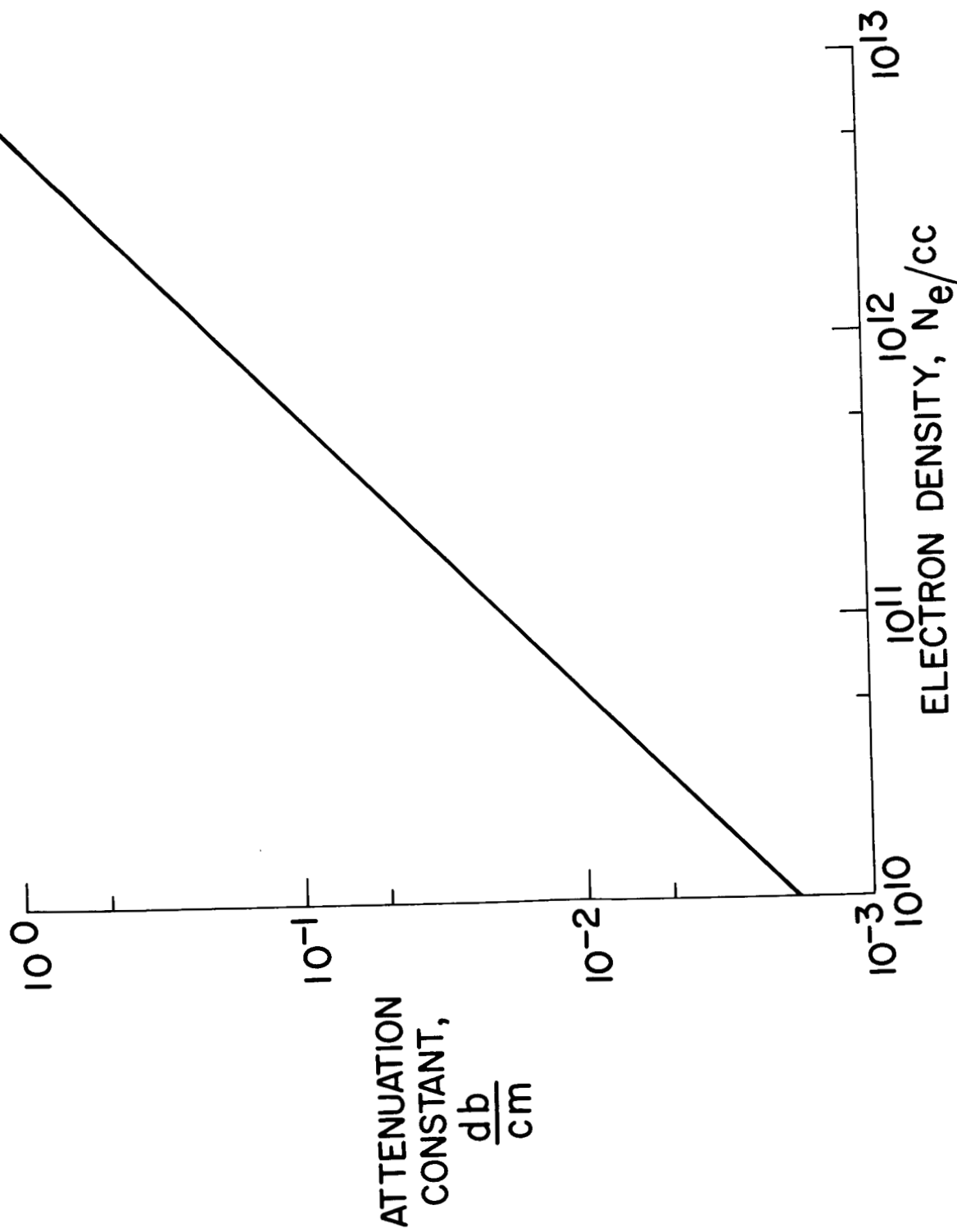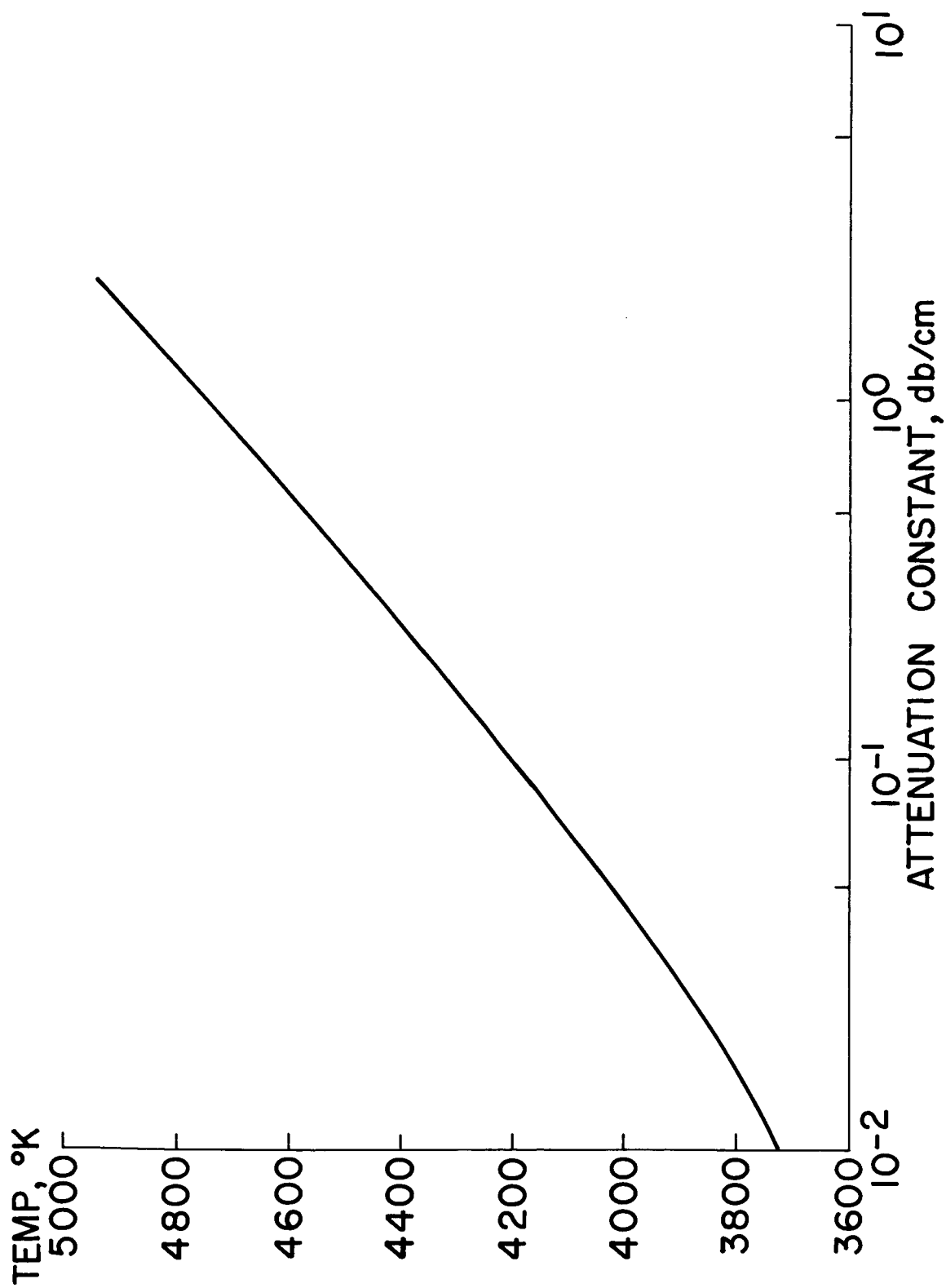
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Figure 6.- Variation of electron density with temperature for the cyanogen-oxygen flame.

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Figure 7.- Dependence of attenuation constant on electron density for a collision frequency of 6×10^{10} sec^{-1} and a wavelength of 4.9 mm.

Figure 8.- Dependence of attenuation constant on temperature for a collision frequency of 6×10^{10} sec^{-1} and a wavelength of 4.9 mm.

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